The Development of the Low Temperature Microgravity Physics Facility

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Abstract. We describe the design and development of the Low Temperature Microgravity Physics Facility, which is intended to provide long duration (4.5 months) low temperature (1.4K) and microgravity conditions for scientists to perform breakthrough investigations on board the International Space Station. The Facility is designed to house two experiments, each occupying a volume of 19 cm diameter and 70 cm long, weighting no more than 6 Kg. In addition to a list of standard available electronics to measure and control temperatures, experimenters can design experiment unique VME standard electronics board to control their own unique sensors. Two identical Facilities are in the plan. The facility will be launched filled with cryogen; and retrieved when the cryogen is depleted, in an approximately 16 to 24 months cycle. Detailed technical capabilities of the Facility will be presented. Technically challenging aspects of the Facility will be discussed.

INTRODUCTION

The Low Temperature Microgravity Physics Facility (LTMPF) is being developed by NASA to provide a long-duration low temperature and microgravity environment on the International Space Station (ISS) for performing fundamental physics investigations. Currently, two experiments have been selected for the first flight and two other experiments for the second flights. More will be selected through bi-annual NASA Research Announcements (NRA) and/or International Announcement of Opportunities (IAO). This program is managed under the Low Temperature Microgravity Physics Facility Project Office at the Jet Propulsion Laboratory. The Facility is being designed to be launched and returned to earth on a variety of vehicles including the H2-A rocket and the space shuttle. On orbit, the facility will be connected to the Japanese Experiment Module's Exposed Facility (JEM-EF). Features of the facility include a cryostat capable of maintaining superfluid helium at a temperature of 1.4 K for 5 months, resistance thermometer bridges, a multi-stage thermal isolation system, thermometers capable of pico-Kelvin resolution, DC SQUID magnetometers, passive vibration isolation, and magnetic shields with a shielding factor of 80dB. The majority of electronics is housed within two VME chasses operating under VxWorks operating system. Technically challenging areas in the design effort include the following:

1) Light weighting of all subsystems to maintain the mass under 500 kg.
2) A dewar with long cryogen life that survives several launch and test cycles without the need to replace support straps for the helium tank.
3) The minimization of heat generated in the sample stage caused by launch vibration
4) The design of compact and lightweight DC SQUID electronics.
5) The minimization of RF interference for the measurement of heat at pico-Watt level.
6) Light weighting the magnetic shields.
7) Implementation of a modular and flexible electronics and software architecture.

The first launch is scheduled for mid-2004, on an H2-A Rocket Transfer Vehicle, out of the Tanegashima Space Center of Japan. Two identical facilities are in the plan. While one facility is onboard the ISS, the other is re-integrated on the ground with new experiments. When the cryogen of the facility in space is exhausted, the facility will be swapped with the other facility with the new experiments. A total of 20 science missions are envisioned over the next 20 years.

The LTMPF system shown in Figure 1 consists of the liquid helium dewar, two VME Experiment Control Boxes (ECB), the radiator, the passive vibration isolation system and the support structure. The Facility is interfaced to the JEM-EF via the Payload Interface Unit (PIU). During launch it is attached to the carrier via the Flight Releasable Attachment Module (FRAM). In the following, the design of each subsystem is discussed in detail:

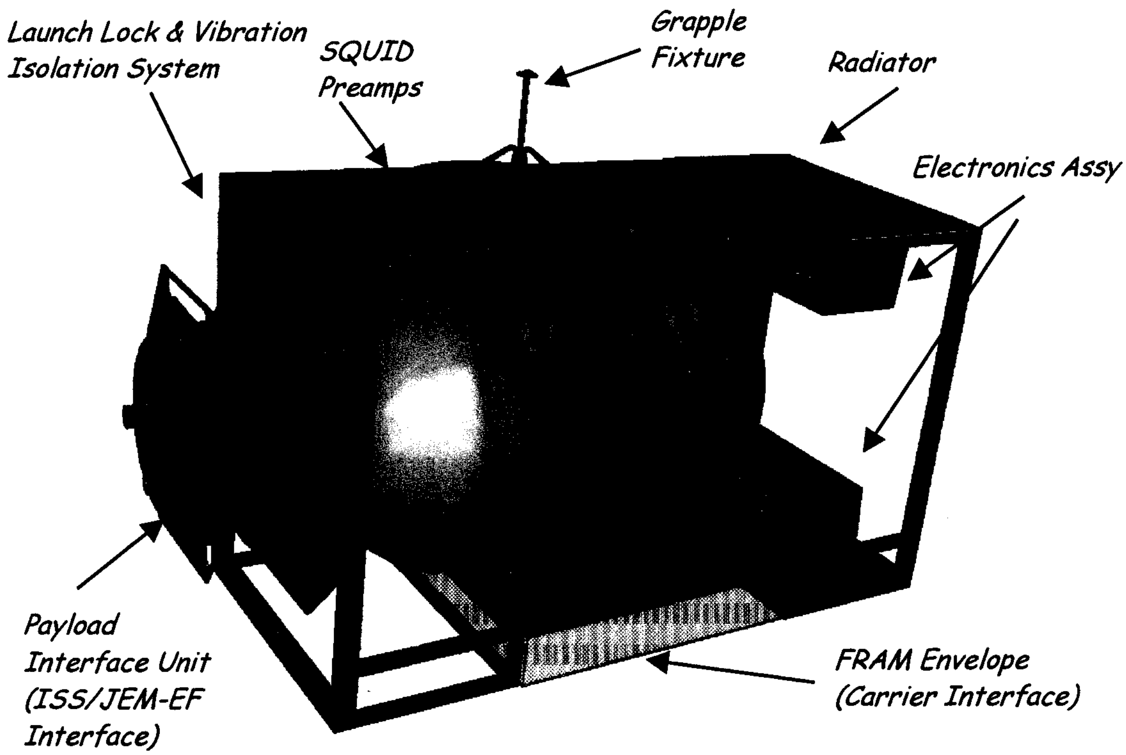

Figure 1. Drawing of the Facility

Dewar

LTMPF requires a light weight dewar, which can provide 5 months of operation with 150 liters of liquid helium. A research and development dewar with two vapor cooled shield was built by Ball Aerospace and Technology Corporation. It has achieved comparable performance. The LTMPF design is based on this design. The core of the design of such a high performance dewar is the support strap system used to suspend the cryogen tank inside the vacuum space of the outer tank. A design using twelve fiber glass straps was adopted to adequately support the cryogen tank during launch while providing enough thermal isolation for the dewar to last for 5 months. The thickness of the fiberglass straps was sized to prevent fatigue failure through 5 cycles of tests and launches.

Similar to other space flight dewars, a porous plug is used as a phase separator, which allows the cryogen to be retained while allowing the vapor to be vented to space [1]. Since the operation of the porous plug is based on the fountain effect of superfluidity, the dewar temperature must be maintained below the superfluid transition temperature at all times. If launched from a Space Shuttle, after the dewar is filled and the shuttle cargo bay doors are closed, the dewar temperature will gradually rise on its own from its initial temperature of 1.4 K. To allow for the possibility of launch delay, the time it takes to warm to the superfluid transition temperature (2.177 K) must be longer than 160 hours. To solve this long launch hold time requirement, an additional valve is added to valve off the porous plug during last cool down. This will allow the VCS to be cooled to < 40 K without heating up the helium in the cryogen tank. Thermal analysis is on going. Other means of extending the launch hold time is being explored.

Similar to previous flights of helium dewars, a vent valve is opened once the Facility is in space. A battery-operated baro-switch is used to operate the valve.

Radiator

Although a cooling loop is provided as part of the JEM-EF interface, due to the necessity to maintain a low vibration environment in the Facility, a radiator is used to get rid of the heat rather than the cooling loop. Currently, the ECBs are anticipated to generate approximately 300 W of power. A heat pipe embedded radiator design is adapted from a previous flight project. Although this design is capable of satisfying the heat extraction requirement when the electronic boxes are on, it may cool the electronics to an unacceptable temperature when the power to the experiment is turned off after the depletion of the cryogen. This period is anticipated to be half a year to a year long. During this period, 100 W of power is provided by the ISS to keep the electronics to within an acceptable temperature range. Currently, LTMPF is actively optimizing the radiator design using the ISS thermal model to meet this requirement.

Vibration Isolation

To satisfy the stringent low g requirement of LTMPF, a passive vibration isolation system will be installed between the PIU and the rest of the facility. During launch, the entire weight of the PIU will have to be supportted by some other means. A locking mechanism is designed as part of this vibration isolation system to lock up the PIU, so that it can be supported during launch. Modeling of this passive vibration isolation system was done using the SIMULINK software package of Matlab and a characteristic acceleration input spectra of the ISS. Its performance was shown to meet the requirements.

Probe

The probe is the thermal and mechanical interface between the dewar and the science instruments. It consists of the vacuum can, the magnetic shield surrounding the vacuum can, the thermal mechanical structure that supports the science instrument and the SQUID housings. The design of each of these components is discussed briefly below:

1. Vacuum Can and the Adsorption Pump

The vacuum can's main function is to provide a high vacuum so that the science experiment and its sensors are thermally isolated from the temperature variations of the dewar. Maintaining good vacuum in a cryogenic environment should be an easy task since most gases will freeze on the wall of the vacuum can. However, it was found in previous flights that under strong vibration such as during launch, the science instrument can heat up to an unacceptable temperature. This is a consequence of the good thermal isolation achieved and the heat generated due to flexing of components in the science instrument. During these previous launches of a similar facility, it was necessary to fill the vacuum can with 3He exchange gas to thermally short the science instrument to the helium tank. The exchange gas was subsequently vented to space. An adsorption pump, with activated charcoal, was implemented to maintain the high vacuum. The adsorption pump as well as its operation sequence is inherited. We refer the reader to ref. [2] for a detail discussion of the adsorption pump.

2. *Thermal Mechanical Structure*

In parallel to using an exchange gas to mitigate launch heating, a parallel approach is taken to make the support structure of the science instrument rigid. In the previous flights discussed above, a contributing factor to the high launch heating effect was that the resonance frequency of thermal mechanical structure was very close to the resonance of the dewar. This intensifies the flexing of the science instrument. If the resonance frequency of the thermal mechanical structure (with the science instrument installed) can be made much higher than the dewar resonance, the heating effect can be mitigated. This approach was successfully implemented by W. Cui et al. [3].

Figure 2 below shows a picture of the thermal mechanical structure consisting of three thermal isolation stages. The support struts of each stage form a hexapod structure, which is known for its rigidity in all six degrees of freedom (3 translational and 3 rotational). The resonance frequency of this structure was measured to be 86 Hz with a 6.2 kg mass supported at the end. This is higher than the expected resonance frequency of the dewar (40 Hz). This structure survived a launch-level vibration test of 7.7 g rms random vibration at the base support plate.

The thermal mechanical structure also provides 1 nano K stability to the science instrument. Each thermal isolation stage is required to isolate thermal disturbance by a factor of 1000. Using high purity aluminum for the stages and stainless steel for the support struts, this required performance is demonstrated by a thermal model. A real measure of this isolation factor is planned.

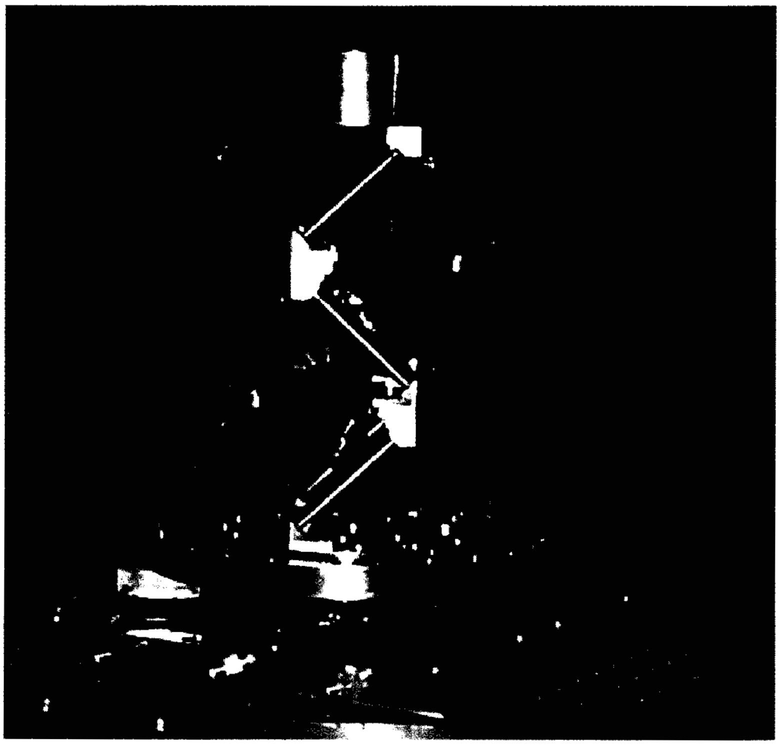

Figure 2. A picture of the probe.

3. *Magnetic Shields*

In most applications using SQUIDs, the dewar is usually surrounded by a magnetic shield made of high permeability material. The shield allows the SQUID to be cooled in a low magnetic-field environment, which is necessary for low noise performance. Due to the size of the dewar, this type of shield is necessarily heavy. A conservative estimate of the weight is about 30 kg. To reduce weight, we have decided to locate the magnetic shield outside the vacuum can of the probe rather than outside the dewar. Because this shield is located in a cold region of temperature below 4 K, a special magnetic material [4], Cryoperm 10, is used. This material is known to retain its high permeability at low temperature. The weight of such a magnetic shield is estimated to be 6 kg.

4. SQUID Housing

A commercial DC SQUID with its niobium housing will be qualified for flight through vibration test and screening for low noise performance and high input coil critical current. In addition a magnetic shield made of Cryoperm 10 material will be built and installed around the SQUID housing. A prototype of this shield was built and tested. An additional 40 dB of shielding was demonstrated for low frequency noise such as that induced by moving through Earth's magnetic field.

The housings are installed on their own thermal isolation stage, separated from the thermal isolation stages of the science instrument. This allows the SQUIDs to be heated through their transition temperature, if it is necessary to drive out any trapped flux.

Electronics

The LTMPF electronics provide the basic thermometry and environmental needs for Principal Investigators (PIs) to perform their experiments in a long-duration microgravity environment. The architecture of the electronics system is shown in Figure 3 below. It can be divided into several components:

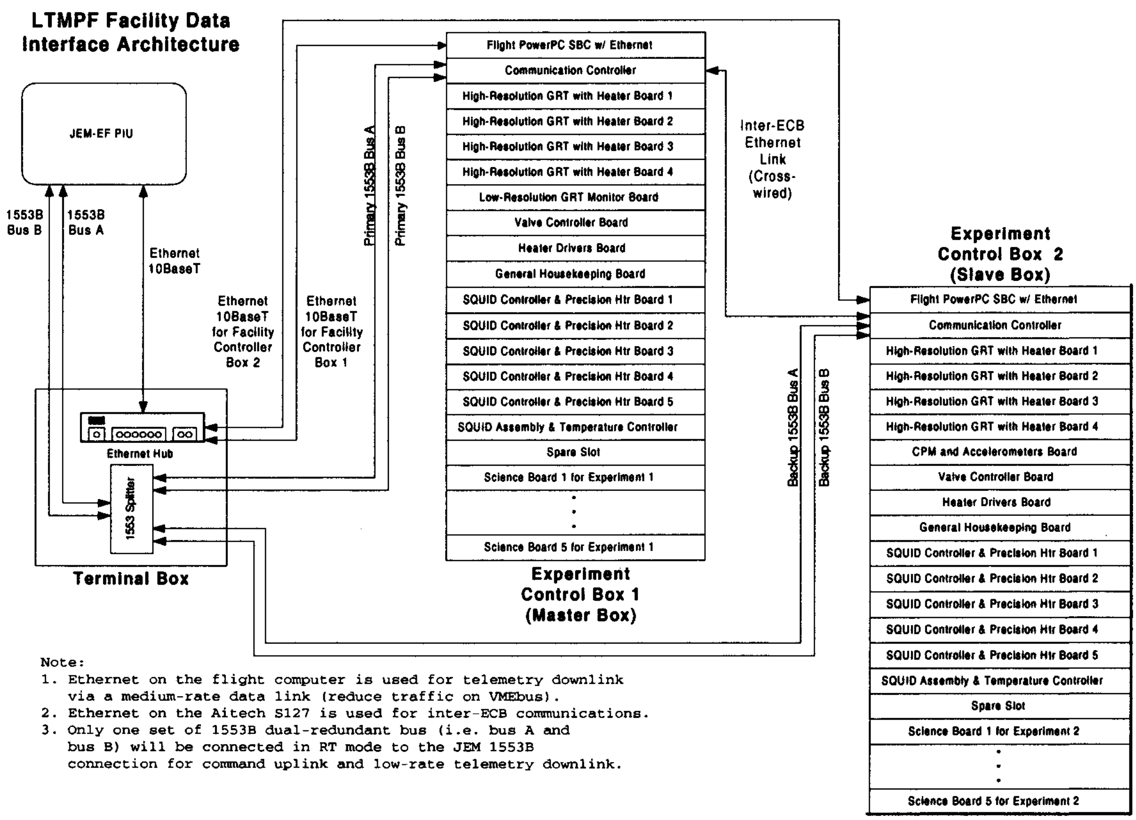

Figure 3. The architecture of the electronic subsystem.

1. Computing

One radiation-tolerant host computer is planned in each of the Experiment Control Box (ECB). The main function of the computer board is to provide the data interface to the ISS as well as communication with the various electronics boards via the VME back plane for operating the Facility and experiments. The computer board will be based on PowerPC architecture with an Ethernet interface for telemetry downlink. The LTMPF Flight Software operates on the two computer boards and the software functions are described in the software section of this paper. In addition to the host computer, each ECB also has a communication controller to provide the 1553B command, time broadcast and low rate telemetry interface as well as an Ethernet link for communication between the two ECBs. The electronic system architecture is shown in Figure 3.

2. Thermometry

Two types of thermometry electronics are provided in the facility for interfacing with two types of sensors. The first type is the Germanium Resistance Thermometer (GRT), with a temperature resolution of $5\mu K/\sqrt{Hz}$. This resolution has already been demonstrated in a prototype. The second type is the High Resolution Thermometer (HRT) [5], based on reading the magnetization of a magnetic material using a Superconducting Quantum Interference Device (SQUID). This type of thermometer routinely achieved a temperature resolution of $0.15\ nK/\sqrt{Hz}$. During previous flights mentioned above, an RF SQUID was used for the HRT readout. In LTMPF, the plan is to upgrade to an even higher resolution DC SQUID.

3. Housekeeping

Housekeeping electronics includes valve (pressure and gas valves) control, temperature sensor readouts and EMI-shielded power conversion from the incoming ISS power supply.

4. Space Environment Monitors

Charged particle monitors are provided to monitor the radiation environment during mission operations. Since charged particles can provide undesirable heating to the experimental cells, this monitor can provide independent data for post-mission science analysis. Three-axis accelerometers will be obtained from the Space Acceleration Measurement System (SAMS) project to provide data on the quality of the microgravity environment.

Software

The LTMPF Flight Software Set includes the LTMPF Flight Software, DSP software and FPGA software. The LTMPF Flight Software is designed for use in each of the two host computers resident in two separate ECBs. Each box is responsible for controlling one of the two experiments integrated in the LTMPF. The DSP and FPGA software provides independent closed-loop control on each board and data communications between the board and the host computer.

The LTMPF Flight Software is implemented on two identical Single Board Computers (SBC) in two ECBs of the LTMPF. The software architecture is shown in Figure 4 below. The LTMPF Flight Software has four major functional areas:

1. *Command and Data Handling*

The command and data handling software provide interfaces to the ISS for command and telemetry. The commands are received from the Low Rate Data Link (LRDL) through a 1553B dual-redundant bus. Telemetry packets are sent to either the LRDL or the Medium Rate Data Link (MRDL) through an 802.3 10BaseT Ethernet bus. Only one of the telemetry links will be active at a time.

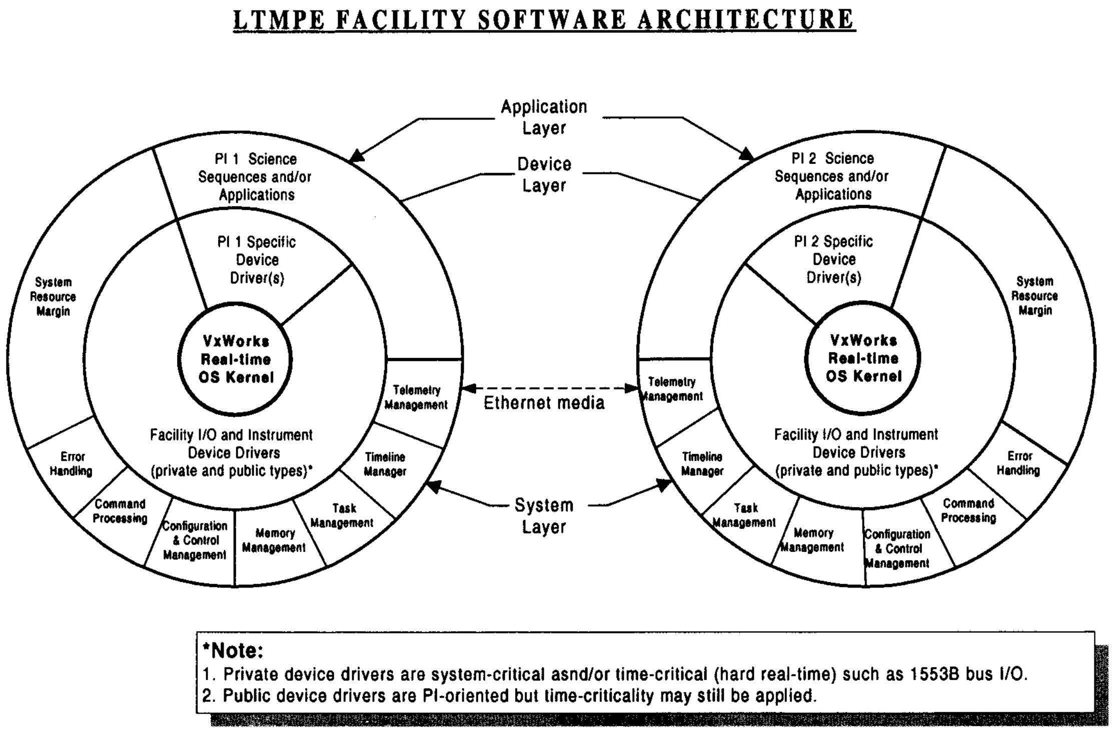

Figure 4. The software architecture.

2. *Communications between the two ECBs*

The communications between the two ECBs provide the capability to update status between the two ECBs. The interaction between the two ECBs is required in two unique scenarios:

The first scenario is best described as a "master" and "slave" interaction between the two ECBs. One of the boxes is assigned as the "master" which is responsible to maintain command and telemetry interface with the ISS. This assignment will happen autonomously at power up. The telemetry packets (include telemetry from both "master" and "slave" SBCs) are assembled in the "master" box for downlink to the ISS interface. The "slave" box will interact with the "master" box for commands and telemetry. The "master" and "slave" role can be toggled by a ground generated control command in the event the autonomous power up selection proves inadequate.

The second scenario is to duplicate the current status of the experiments running in the two separate chasses. In the event of a system failure in one of the two boxes, the operational box can quickly provide the status of the failed system. Also, after the failed system is recovered, it will make an attempt to return to its previously known state (before failure) and continue operations.

3. Task and Timeline Management

This functional area provides task and timeline management functions for facility and science-specific tasks or sequences. PIs are provided with the capability to issue commands from a ground station to spawn and stop science tasks without affecting the operations of the facility. Timeline management permits specific science tasks or sequences to start at a specific time in the future. This feature will help PIs to prepare long-term plans for their experiments.

4. Control and Data Acquisition of the Facility and Science Electronics

This functional area provides an interface for the facility and PI-specific electronics boards. Each PI interacts with the facility and PI-specific electronics in the ECB in order to perform an experiment. All the electronics boards are connected to the SBC through a VMEbus, and the SBC is also the bus controller for the VMEbus in both ECBs.

The remaining two components of the LTMPF Flight Software Set (DSP and FPGA software) are used to control the thermometry boards in terms of control loops and data acquisitions. The DSP software is stored on the SBC initially. When the two ECBs are turned on, DSP software is downloaded to all the necessary electronics boards. All communications between the VME electronics boards and the SBC are done through the VMEbus backplane.

Operations

During the several days that it takes the launch vehicle to match the ISS orbit and then dock, the LTMPF dewar will have cooled down to its normal operating temperature. The only crew interaction with the LTMPF occurs as they use Station, Shuttle, and Japanese robotic arms to transfer the LTMPF from its carrier to its berth on the JEM-EF. Once its connection to the ISS has been verified the system will be operated by ground controllers at JPL and the PI institutions. The two experiments will be operated simultaneously by their respective science teams and continuously (24 hours a day and 7 days a week) until the helium in the dewar has boiled off in roughly 5 months. During this time all nominal and contingency operations will be operated via telescience. The LTMPF planners will schedule experiments appropriate to the expected environment and work with the ISS team to coordinate optimal data-taking periods in which the Station is in a Microgravity Mode and not subjected to a large flux of charged particles or ISS-generated RF noise.

CONCLUSION

The design of the LTMPF system discussed above will provide a long duration low temperature and microgravity environment for the scientific community to perform breakthrough scientific research on the ISS. In addition, the Facility staff will provide a user-friendly infrastructure including management and technical support so that access to space will become routine and easy for the science investigators.

ACKNOWLEGEMENTS

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